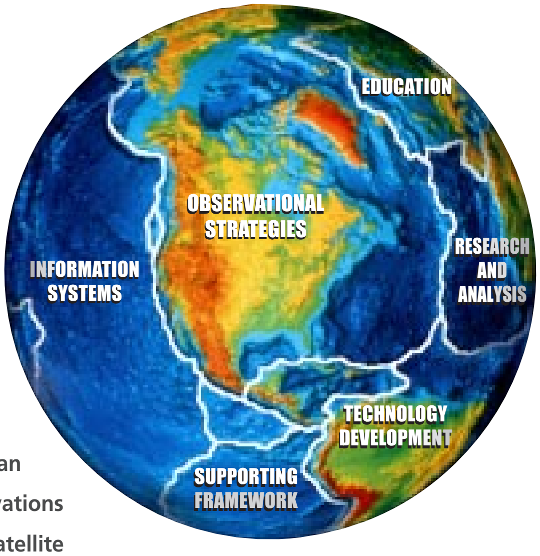
Recommendations for an Integrated Program for Solid Earth Science

To make substantial progress toward answering each of the six challenges for solid-Earth science, NASA must formulate a broadly conceived program with both near-term goals and clear steps toward longer-term objectives. A fully realized program contains elements that encompass all of the following aspects:

- Observational Strategies
- Research and Analysis
- Information Systems
- Technology Development
- Supporting Framework
- Education



By weaving each of these essential elements into an integrated program architecture, the long-term goals of understanding the solid Earth and achieving predictive capabilities can be attained. NASA's role in observations is primarily the development of satellite missions, but such projects cannot be as effective as possible without complementary terrestrial observations and the requisite partnerships with other programs and agencies. A dedicated research and analysis program is a critically important core activity, to ensure that newly acquired data are fully analyzed, to provide the new ideas for instrument and mission development, and to foster unexpected scientific discoveries. This effort should include significant investments in computation and modeling for testing theories and predictions. A number of observations needed over the next two and a half decades require a continuing investment in advanced technology development. This modular yet broadly interlinked program architecture offers flexibility to change as scientific discoveries and programmatic requirements dictate.

This strategy builds on current capabilities and resources. It requires data from missions and instruments that have recently flown, that are currently flying, and that are planned to be launched in the very near future (e.g., ASTER, SRTM, SAC-C, CHAMP, GRACE). It also relies on data from missions that are currently supported by other scientific disciplines such as the Global Precipitation Mission and the River Discharge and Cold Regions Exploratory Missions. This strategy leverages collaborations and partnerships to the largest extent possible with other government agencies, the private sector, and the international community. The focus in the following section is largely on new observational requirements that have been identified by the SESWG and on the implications for required technology investments.

Observational Strategies

Understanding the solid Earth and moving toward predictive capabilities where appropriate requires a broad observational strategy, incorporating numerous methodologies (including spaceborne and ground measurements), technological advances, and complementarity among observations. The SESWG recommends the following seven observational strategies to address the fundamental solid-Earth questions that frame this report.

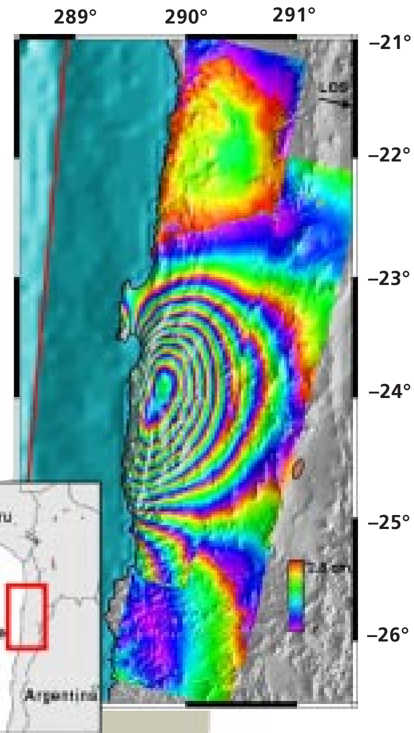
Recommended Observational Strategies

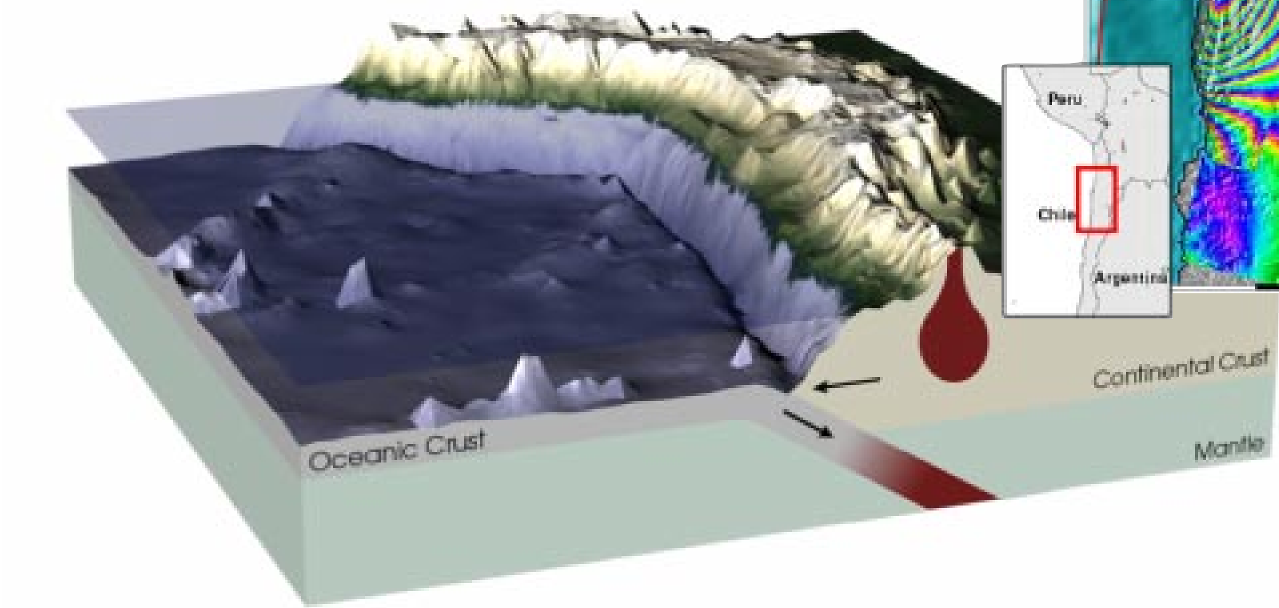
1. *Surface Deformation*
2. *High-Resolution Topography*
3. *Variability of Earth's Magnetic Field*
4. *Variability of Earth's Gravity Field*
5. *Imaging Spectroscopy of Earth's Changing Surface*
6. *Space Geodetic Networks and the International Terrestrial Reference Frame*
7. *Promising Techniques and Observations*

1. Surface Deformation

The land surface deforms both vertically and horizontally as a result of a number of geological and geophysical processes, many of which have significant implications for natural hazards. Episodic deformations arise from earthquakes and volcanic activities whose measurements are essential to understanding and mitigating these natural hazards. Aseismic deformation before and after earthquakes can now be measured as a result of space technologies and are key to understanding earthquakes and the Earth's internal dynamics. Post-glacial rebound occurs by slow, large-scale deformation that provides great insight into the mechanical properties of the solid Earth. Local land subsidence due to groundwater withdrawal, river and coastal erosion and deposition, landslides, and debris flows all impact the land surface and affect human livelihood. Continuous perturbations arise from solid-Earth tides and loading by variations in atmospheric pressure, oceanic circulation, and the distribution of water and ice.

Centimeter to millimeter/year accuracies are necessary to make meaningful detection of these land changes. The space geodetic techniques of satellite laser ranging, very-long-baseline interferometry, and geodetic GPS have in the past decade successfully measured relative horizontal motions among tectonic plates, as well as differential crustal movements along many active plate boundaries. In recent years they have also detected the postglacial rebound signal and the coseismic and postseismic deformations associated with several large earthquakes.





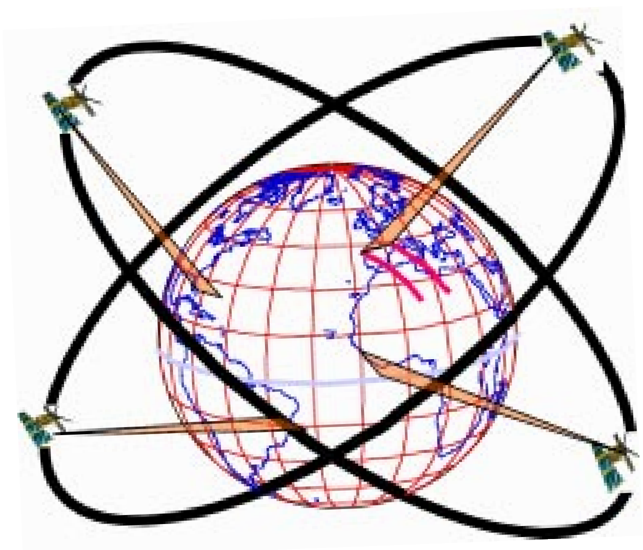
(Below) Three-dimensional rendering of subduction of the Nazca plate beneath western South America. (Right) Coseismic surface deformation from the 1995 magnitude 8.1 Antofagasta, Chile, subduction zone earthquake determined by InSAR. Each color cycle indicates 2.8 cm of motion in the satellite line-of-sight (LOS) direction. The horizontal projection of the LOS vector is indicated by the arrow at the top right. The red line indicates the boundary between the Nazca and South American Plates at the bottom of the oceanic trench.

Complementary to the techniques described above, which are typically continuous in time but limited to specific locations, two new space geodetic techniques provide spatially continuous observations that are typically limited in temporal coverage: InSAR and laser altimetry (lidar). Both have proven successful in proof-of-concept airborne experiments, and InSAR has further demonstrated its great utility from space in detecting land surface changes caused by earthquakes, movement of magma at depth, ice-sheet motion, and land subsidence. InSAR measurements of surface deformation rely on repeated acquisitions of radar images, and satellite platforms permit a synoptic view of a host of geologic processes on a global basis.

The goal of the surface deformation observational strategy is to measure spatially continuous displacements of the Earth's surface on both temporally and globally comprehensive bases. Repeat observations must resolve rapid deformational processes such as earthquakes, volcanic eruptions, glacial flow, and regions of devastated infrastructure

due to fires and earthquakes in urban areas. The ability to map quickly these regions of devastation will substantially improve capabilities for rapid emergency response to these destructive forces. It is important as well to measure slow deformational processes such as interseismic strain accumulation, magma chamber pressurization, surface displacements from migration of crustal fluids (e.g., water and oil), and motions of the ice sheets.

Modeling to date indicates that accuracies of 1 mm/yr over 50-km horizontal scales are needed. Such a capability will permit an assessment of how slow transient events (e.g., modest strains over large areas) relate to earthquakes, distinguishing between strain accumulation on a single fault from strain on multiple faults, and accurate determination of the nucleation of earthquakes and the effects of fault asperities on earthquake slip.



Studies show that, from a constellation of InSAR satellites, deformation maps can be made at daily intervals or better. One concept using four satellites in an enhanced low Earth orbit (1321 km altitude) would allow 100% of the Earth to be revisited every 16 hours. The long-term goal of hourly global access may be achieved by low-Earth or geosynchronous constellations of InSAR satellites.

Measurement requirements and suggested mission phasing are:

• ***Immediate (1–5 years)***: A single dedicated InSAR satellite operating at L-band, with left/right-looking capability and weekly access to anywhere on the globe. Such a mission should include precise orbit determination and ionospheric correction capabilities. This mission should achieve accuracies of 1 mm/yr surface displacement over 50 km horizontal extents in selected areas. Displacement maps should cover 100-km-wide swaths. Continuous ground GPS observations will provide important complementary information.

Supporting research and analysis should include time-dependent modeling of local fault systems, including numerical mechanical models, pattern recognition, and visualization.

• *Near Term (5–10 years):* A constellation of InSAR satellites capable of producing deformation maps at nearly daily intervals. Maps should extend several hundred kilometers in swath width and provide full vector surface displacements at accuracies of submillimeter per year over 100-km spatial extents and 1-m spatial resolution. Complementary ground and seafloor geodetic observations should continue.

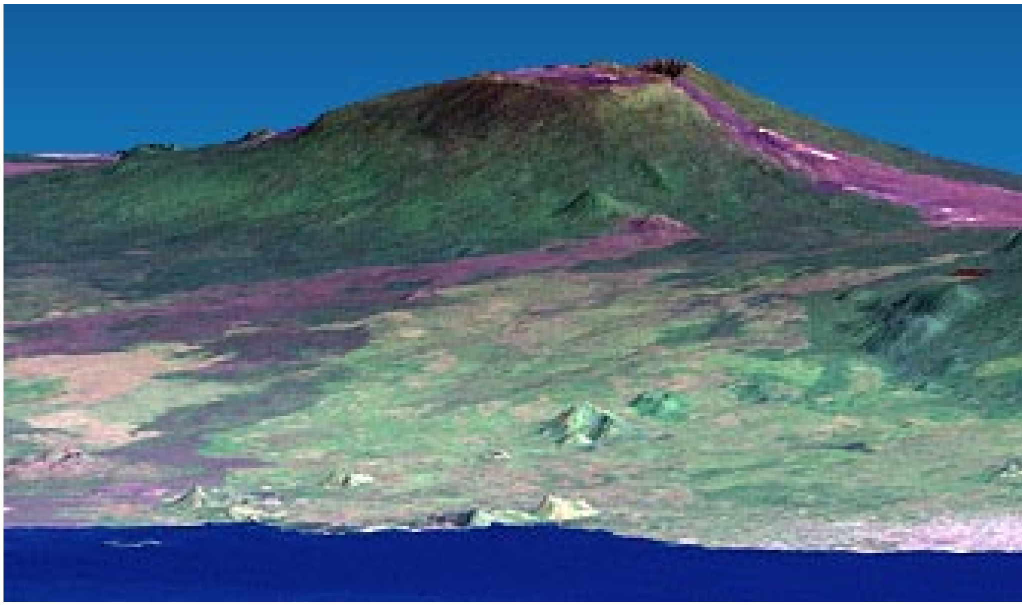
Supporting research and analysis should include assimilation in near-real time of observations into models of fault systems, volcanoes, and the crust–mantle system. The goal should be an understanding of time- and stress-dependent crustal and mantle properties.

• *Long term (10–25 years)*: Hourly global access from a constellation of InSAR satellites in low Earth or geosynchronous orbits. There should be an increase in the density of continuous ground and seafloor geodetic observations.

Supporting research and analysis should target near-term forecasting of such natural hazards as earthquakes, volcanic eruptions, and landslides. Fully three-dimensional, nonlinear, spherical, time-dependent models of the solid-Earth system should be coupled to and able to assimilate continuous streams of new data.

2. High-Resolution Topography

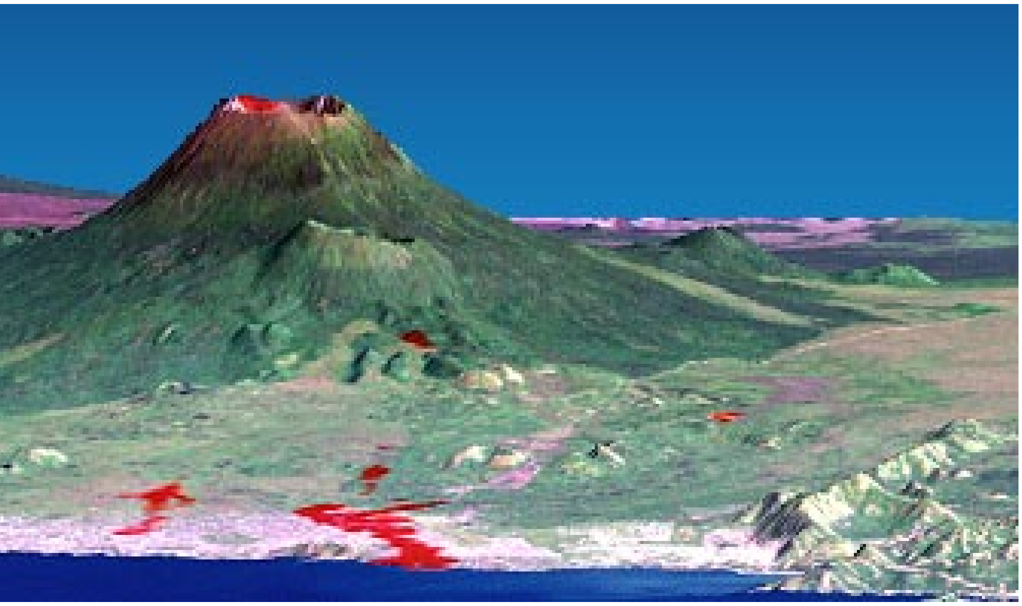
Accurate measurements of topography and topographic change are fundamental to most of the science themes addressed in this report. Topographic measurement capabilities have advanced significantly in recent years. Radar observations from the



The Nyiragongo volcano in the Congo erupted in early 2002 and subsequently sent streams of lava into the city of Goma (lower right, on the north shore of Lake Kivu). More than 100 people were killed, and hundreds of thousands were forced to flee. This computer-generated visualization combines Landsat and ASTER satellite images and an elevation model from SRTM.

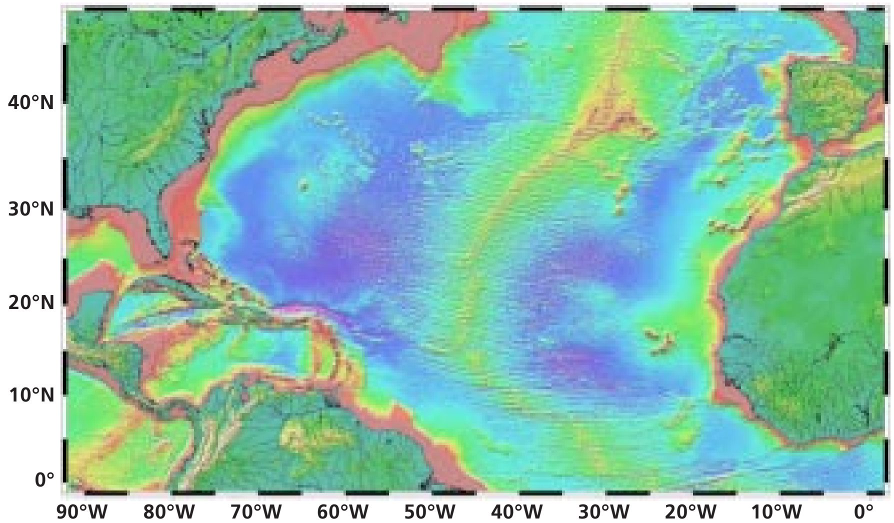
Shuttle Radar Topography Mission (SRTM) acquired in early 2000, in cooperation with the National Imagery and Mapping Agency (NIMA), are being used to produce a nearly global digital topographic map with 30-m horizontal precision and 10-m vertical accuracy. A new generation of global digital elevation models with sub-meter-scale accuracy is needed to provide more accurate and frequently measured topography. Special attention must be paid to steep terrain (the sources of landslides and some floods), because such terrain was only partially imaged by SRTM. Measurement of transient topography, such as the surfaces of rivers in flood, is also a key need. Airborne scanning laser altimeter and InSAR techniques provide local to regional digital elevation models with meter- to tens-of-meters-scale resolution at decimeter- to meter-level vertical accuracy. The Shuttle Laser Altimeter (SLA) demonstrated spaceborne land surface altimetry at meter-level vertical accuracy, and the upcoming Ice, Cloud, and Land Elevation Satellite (ICESat) missions will provide comprehensive profile sampling of the Earth's land and ice elevations at decimeter- to meter-level accuracy. SLA and ICESat are profiling systems with along-track resolutions of 700 and 175 m, respectively.

Because direct remote sensing of seafloor topography is not feasible, our historical understanding of the morphology of the 70% of Earth's solid surface that lies beneath the oceans comes from observations made with single- and multi-beam echo sounders mounted on oceanographic research vessels. The resulting data coverage is highly variable in coverage and resolution. To date, only 0.1% of the oceans has been surveyed at 100-m horizontal resolution, and large tracts of the seafloor (such as most of the southern oceans) have not been mapped at all. Seafloor topography can be inferred indirectly at lower (~10 km horizontal) resolution, however, from satellite altimeter mea-



Additionally, ASTER image data were used to supply a partial map of the recent lava flows (red), including a mapping of their intrusion into Goma. Topographic expression has been exaggerated vertically by a factor of 1.5 for this visualization. Nyiragongo and other nearby volcanoes sit within the East African Rift Valley, a zone where tectonic processes are faulting, stretching, and lowering the Earth's crust. Volcanic activity is common here, and older but geologically recent lava flows (magenta in this depiction) are particularly apparent on the flanks of the Nyamuragira volcano (left background).

surements of the sea surface (i.e., from the marine geoid). Recent global seafloor maps produced from spaceborne altimetry provide a large-scale view of Earth that is lacking from traditional sources and, in fact, has provided substantial new insight into the seafloor structure and geological history of remote parts of the globe. Forthcoming developments in radar and laser altimeters, constrained by selected higher-resolution shipborne measurements, could improve the resolution of global seafloor topography and morphology to a point that would substantially advance our understanding of volcanism, faulting, sedimentation, and plate evolution in oceanic regions.



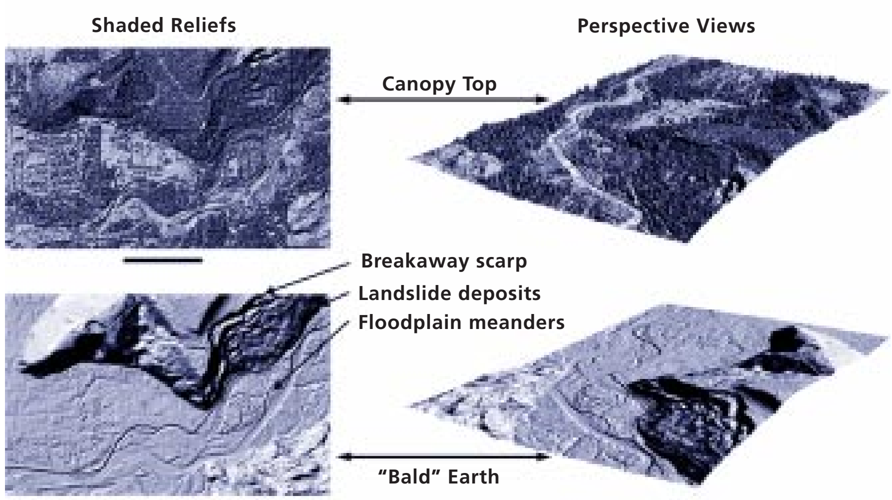
Topography of the ocean floor derived from sparse ship soundings and dense satellite altimeter measurements of ocean surface height (i.e., geoid height). The 10-km resolution topography reveals the broad features of seafloor spreading such as the median valley along the ridge axis, the transform faults, and the thermal subsidence of the cooling oceanic lithosphere. Higher-resolution topography can be obtained by additional ship soundings and/or a new higher-resolution satellite altimeter mission.

A specific new application of topographic measurements of the land surface is to obtain landslide inventories. Landslides are primarily associated with triggering events, such as rainfall, snowmelt, or earthquakes. The statistics of these events, however, are poorly documented. Since large landslide events are rare, it is essential to obtain inventories on a worldwide basis. One goal is to automate the measurement of landslide areas and volumes using differences in topographic observations prior to and after each landslide event.

Topographic measurements can also be used to quantify sediment deposition in arid areas during a flood. Analyses of the topography of alluvial fans before and after a flood will give the volume of sediment deposited.

Despite these advances in both methodology and analysis, topographic measurements necessary to achieve solid-Earth science goals remain inadequate due to limits in spatial resolution, vertical accuracy, extent of coverage, and frequency of repeat observations. Because topographic data and their temporal changes are fundamental to diverse solid-Earth disciplines, the observational requirements are discipline specific. Three classes of observations encompass the diversity of requirements: improvements in vertical accuracy to 0.1 m in targeted regions (with frequent repeats), one-time global mapping at 0.5-m vertical accuracy to define the present topographic template which surface processes and tectonics modify, and improved mapping of ice sheets and glaciers. Attainment of a process-based understanding and prediction of natural hazards is critically dependent on the determination of highly resolved and accurate topography.

Vertical accuracy refers to the ground or water surface whether or not vegetation cover is present (i.e., the “bald” Earth). For some applications, such as those dependent on local slope or landform shape, the vertical accuracy need be only relative (elevation with respect to an adjacent elevation). For others, such as those requiring regional elevation correlations or change detection, the vertical accuracy must be absolute (with respect to a reference frame).



Vegetation cover and underlying ground topography imaged by high-resolution airborne scanning laser altimetry. Terrapoint ALTMS (Airborne Lidar Topographic Mapping System) data obtained for the Puget Sound Lidar Consortium have 1.8-m horizontal resolution and ~20-cm vertical accuracy (no vertical exaggeration).

Spaceborne swath-mapping laser altimetry (imaging lidar) and dual-frequency interferometric SAR technologies, potentially in combination, hold the greatest promise for achieving these goals. Cross-track InSAR with precision antenna spacing can map topography with centimeter-level resolution. Lidar can measure topographic change over land, rivers, and oceans. The combined use of lidar and InSAR can provide comprehensive characterization of vegetation height and topography of high resolution and accuracy for the "bald" Earth. Considering the readiness level of these technologies and the current status of topographic mapping activities, measurement requirements and suggested mission phasing are:

• *Immediate (1–5 years)*: Production and public distribution of global topographic data from the radar observations acquired by SRTM, launch the ICESat altimeter mission, and demonstrate imaging lidar capabilities in Earth orbit on the Shuttle or International Space Station.

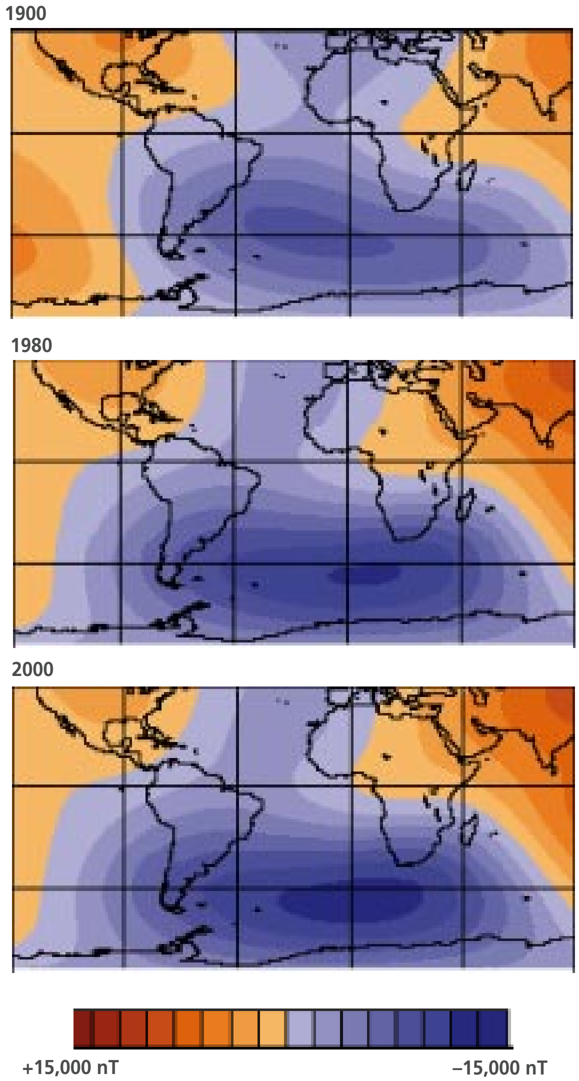
• *Near term (5–10 years):* Global mapping to supercede the SRTM data set. One-time global mapping of the ground surface should be at 2- to 5-m resolution and 0.5-m vertical accuracy. Ice-sheet mapping, to enable data continuity with the ICESat mission, should be at 1-km horizontal resolution, 1-cm vertical accuracy for the ice or snow surface, and a repeat interval of months (for annual changes) to years (for long-term changes).

• *Long term (10–25 years)*: Beginning of a continuously operating, targeted, high-resolution topographic mapping and change detection capability. Targeted local to regional mapping, with global access, at 1-m resolution, 0.1-m vertical accuracy for the ground and water surfaces, and a repeat frequency of hours to years depending on the rate of topographic change.

In addition to these mission activities, an active research and analysis program should establish methods to integrate laser and InSAR observations and to incorporate these new sources of topographic data into studies that unravel the past history of landscape evolution, reveal the interactions of geomorphic processes, and improve preparations for and predictions of natural hazard events. Emphasis must also be placed on the calibration and validation of these new satellite-based sources of topographic data, to ensure that they are appropriately used in landscape studies and modeling, through comparisons to detailed ground-based and airborne measurements of topography and vegetation cover.

3. Variability of Earth's Magnetic Field

Geomagnetism provides one of three space-based techniques to probe the Earth's interior. (The other two are gravity and Earth rotation.) Geomagnetic studies are currently limited by a paucity of observations and attendant difficulty in their interpretation. Recent advances in nanosatellite technology hold the promise for cost-effective geomagnetic constellation operations. The International Decade of Geopotential Research endorsed by the International Association of Geomagnetism and Aeronomy (IAGA) and the International Association of Geodesy (IAG) has played a major role in encouraging programs that have led to the launch of Oersted, Sunsat, CHAMP, and SAC-C over the last five years.



The South Atlantic Magnetic Anomaly strength at 500-km altitude has increased significantly over the last 100 years. In 2000, the magnetic field was about 35% weaker in the South Atlantic than would be expected from a dipole field. This weakness in the field has serious implications for low-Earth-orbit satellite operations, because it impacts the radiation dosage at these altitudes. How much longer will the South Atlantic Magnetic Anomaly continue to grow? How deep will it become? Long-term satellite observations will allow us to model the future evolution of this anomaly.

Constellation measurements provide a number of advantages over single-satellite measurements, including improved tracking of external field variability with local time and latitude, by observing the field simultaneously at a range of local times; improved observation of the main field and short-period temporal variations; and magnetic gradient measurements for the determination of magnetospheric and ionospheric current systems and the determination of an accurate external field model.

The density of the constellation is determined by the requirement to be able to separate spatial and temporal variability of the different components of the field, especially variability of the external field. Furthermore, better measurements of the external field components will lead to higher resolution electromagnetic induction studies of the mid- to deep-mantle and facilitate studies of the relationship between space weather and the Earth's atmosphere. High-resolution main field observations will provide an improved determination of core field secular variation.

Measurement requirements and suggested mission phasing are:

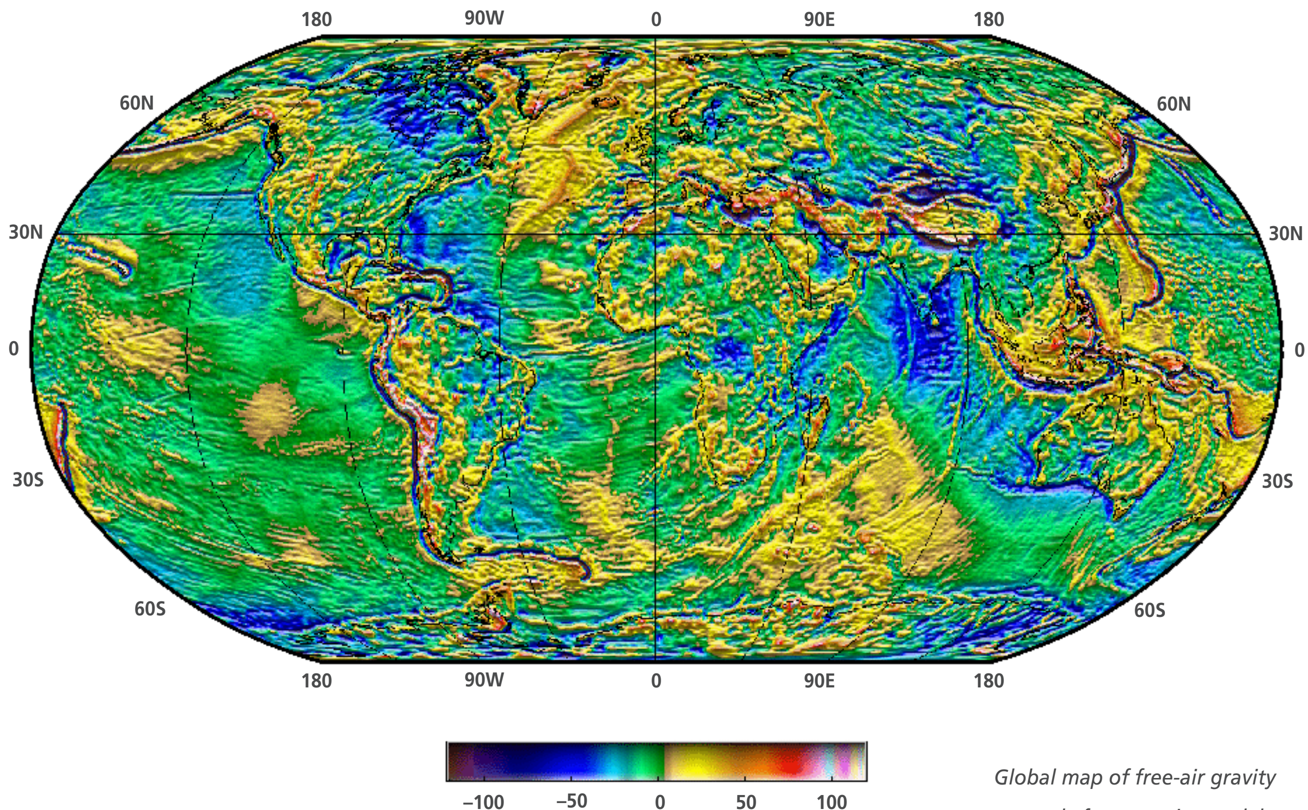
• *Immediate (1–5 years)*: Support of analysis of geomagnetic observations from current satellite missions. A modularized instrument package should be developed to facilitate taking advantage of missions of opportunity.

• *Near term (5–10 years):* Constellation of 4–6 satellites at a range of local times in polar orbit at approximately 800-km altitude.

• *Long term (10–25 years)*: Establishment of a more complete, 12-satellite constellation by adding satellites at lower altitude (300 km) in polar orbits (to enhance study of the crustal field) and at 800 km in a low-inclination orbit (to enhance recovery of mantle electrical conductivity). Technological advancements should include the incorporation of star trackers on magnetometers and improved lifetimes at low altitudes.

4. Variability of Earth's Gravity Field

Satellite gravity measurements have demonstrated the clear importance of determining the spatial and temporal variability of the Earth's global gravity field. The first measurements of spatial and seasonal gravity variability at scales of thousands of kilometers were obtained by laser-tracked geodetic satellites such as LAGEOS I and II. Seasat and subsequent ocean altimetry satellites provided the first high-resolution satellite-derived gravity field over the oceans and yielded the most complete map yet of ocean floor bathymetry. There are now three dedicated high-resolution gravity missions — GRACE, CHAMP, and the European Space Agency's Gravity Field and Steady State Ocean Circulation Explorer (GOCE) — either in orbit or planned. Each mission makes use of a different technique for gravity measurement. The 1997 National Research Council report "Satellite Gravity and the Geosphere" outlined in detail the com-



Global map of free-air gravity anomaly from gravity model EGM96, complete to spherical harmonic degree and order 360. Lighter shades denote higher gravity than average; darker shades, lower gravity than average. The unit is milligal, where 1 milligal ($10^{-5} m/s^2$) is about one-millionth of the Earth's average gravity. The pattern follows tectonic features and also reflects deeper density anomalies. Any time-variable gravity signal would be superimposed on this reference static field.

pelling rationale for temporal measurements of the gravity field to the cryospheric, hydrological, atmospheric, oceanographic, and solid-Earth sciences.

GRACE, a collaboration between NASA and the German space agency, is the first satellite to measure temporal variability of the gravity field on a monthly basis at spatial scales as short as a few hundred kilometers. Although the strongest signals in the temporal variability of gravity are associated with mass transport in the atmosphere, oceans, and land hydrological systems, there are a number of measurements relevant to solid-Earth properties and processes, including lithospheric and mantle structure and glacial and oceanic loading and unloading of the lithosphere. Careful modeling of atmospheric, oceanic, and hydrological contributions will be necessary to resolve the signature of solid-Earth phenomena, as will calibration and validation with ground measurements. In situ ocean-bottom pressure measurements are also a required component of a space-based gravity measurement program so that ocean contributions can be separated from solid-Earth signals. Gravity missions such as GRACE, when combined with high-resolution radar altimetry missions such as Jason, will allow for the identification of the steric component of sea-level variations and the partitioning of water storage among continents, oceans, and ice sheets and glaciers. Combined use of time-variable gravity data and ice-mass data (e.g., from ICESat) can help quantify the mantle

response to past and present glaciation. Because Earth-rotation parameters and gravity anomaly measurements are both manifestations of mass redistribution, geodetic and gravity measurements are excellent examples of synergy, allowing a better understanding of global mass transport in the Earth system.

Future gravity missions using laser interferometric or other high-resolution gradiometry techniques should achieve a sensitivity 100 to 1000 times that of GRACE. With that sensitivity it will be possible to resolve crustal deformation signals, such as mass displacement due to undersea lithospheric strain, vertical motions associated with lithospheric loading and unloading, changes induced by earthquake and volcanic processes, and subsurface aquifer and oil reservoir withdrawal.

Measurement requirements and suggested mission phasing are:

• *Immediate (1–5 years):* Monthly estimation to within 10 millimeters of surface water-equivalent load at a few hundred kilometers spatial resolution using existing satellites such as GRACE.

• *Near term (5–10 years):* GRACE follow-on mission demonstrating satellite-to-satellite laser interferometry technology.

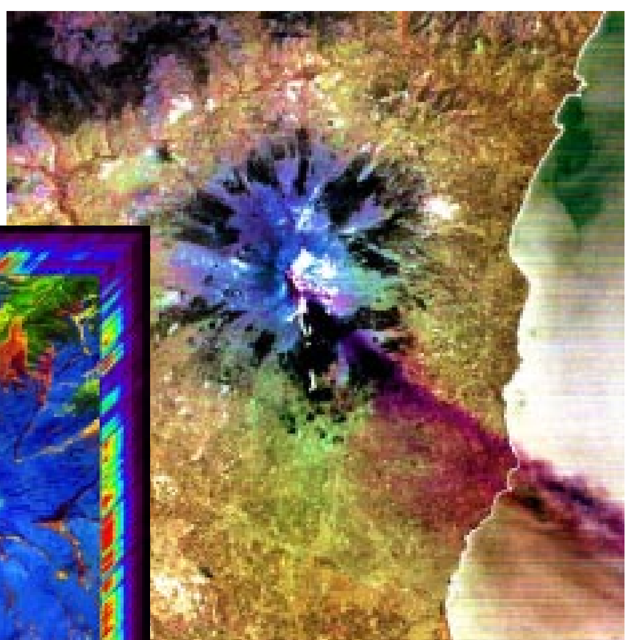
• *Long term (10–25 years):* Gravity measurement improved by 2–3 orders of magnitude in sensitivity using satellite-to-satellite laser interferometry or spaceborne gradiometer technology.

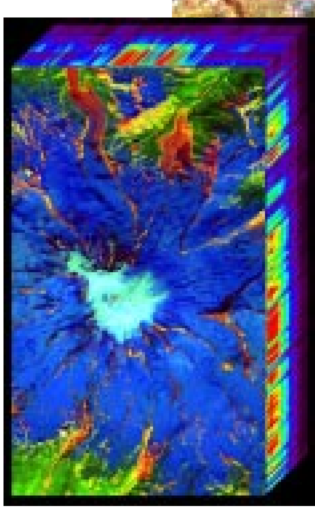
5. Imaging Spectroscopy of Earth's Changing Surface

The Earth's surface is the interface between the atmosphere, hydrosphere, and the solid Earth and is the interface of greatest importance to humankind. Imaging spectroscopy (or "hyperspectral" imaging) can resolve the surface attributes and expression of many of the processes related to natural and human-induced landscape change, volcanism, tectonics, and ice dynamics. Because near-surface materials and their properties often determine a region's susceptibility to such natural hazards as earthquakes, severe storms, wildfires, and volcanic activity, characterizing these materials will contribute significantly to global hazard mapping.

Even in aerial photographs, which represent perhaps the simplest form of remote sensing, it is possible to recognize fire scars, landslides, old ice, and fresh lava. Imaging spectroscopy, in both the solar-reflected (0.4 to 2.5 μm) and thermal portions (3–5 μm and 8-12 μm) of the spectrum, raises this science to a new level because it permits the identification, separation, and measurement of subtle variations reflecting the overlapping molecular absorption and constituent scattering signatures of materials present on the Earth's surface. Hundreds of spectral bands are sometimes required to resolve and map the large number of materials present on the changing surface. In the face of the land surface's complexity, imaging spectroscopy provides a basis for the uniform compositional measurement of the exposed surface of the solid Earth for both basic science and hazards research.

As an example, measurements made by AVIRIS (Airborne Visible and InfraRed Imaging Spectrometer) are serving to define volcanic hazards and to aid in forecasting impending eruptions. AVIRIS data have been used to map subtle changes in near-surface rock chemistry and, thereby, to identify zones of volcanic-debris-flow susceptibility on the basis of rock strength inferred from specific mineralogical indicators of hydrothermal alteration. Debris-flow hazards to downstream communities represent the greatest volcanic threat for loss of life. Identification of susceptible zones could help to reduce this risk. Volcanic ash clouds pose a significant aviation hazard, as ash particles can and have destroyed jet engines. Real-time volcanic plume and ash detection and characterization in both the visible and thermal portions of the spectrum will reduce the risk posed by this hazard and will contribute significantly to our scientific understanding of eruptive processes. Identification of outgassed species near vents and craters provides information on subsurface activity and processes and may ultimately assist in forecasting eruptions. Thermal measurements of land surface temperature, together with simultaneous measurements of the changing emissivity, provide additional critical constraints on magmatic processes and volcanic activity.





(Right) Mt. Etna is one of the world's most active volcanoes and has been studied for centuries from the ground. This ASTER image was acquired during a recent eruption (July 29, 2001) and shows the sulfur dioxide plume (in purple) originating from the summit, drifting over the city of Catania, and continuing over the Ionian Sea. ASTER's unique combination of multiple thermal infrared channels and high spatial resolution allows the determination of the thickness and position of the SO_2 plume. The image covers an area of 24 x 30 km.

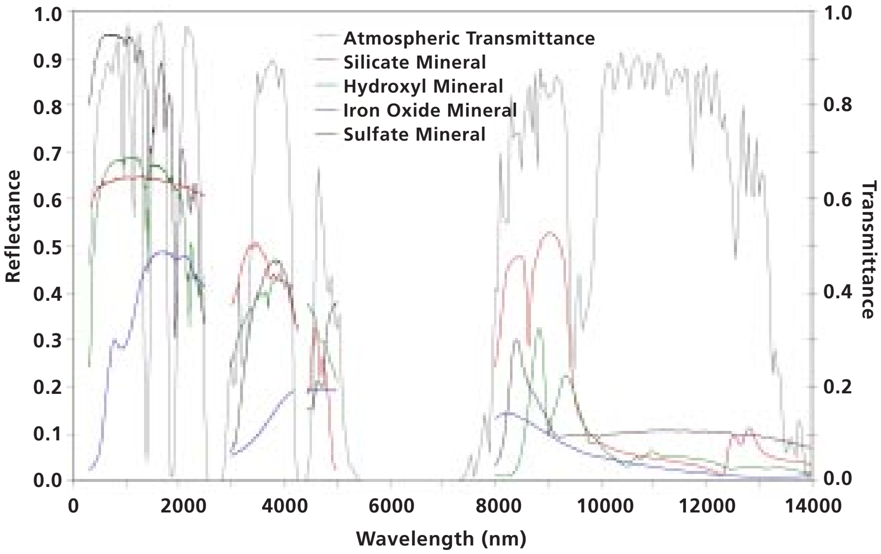
(Left) Mount Rainier, Washington, AVIRIS image cube. The top and right panel show the spectra from 400 to 2500 nm for the edge elements. The face panel (10 x 20 km) shows aspects of the composition of the surface, including frozen snow and ice (light blue), melting snow (dark blue), vegetation (green) and exposed rock and soil (red-brown). The AVIRIS spectra of this data set have been used to measure the snow and ice composition and melting status. The exposed rock composition and alteration has been determined for volcanic collapse hazard assessment.

In arid environments, dust storms, sand storms, and migrating dunes pose hazards that can be effectively tracked via imaging spectroscopy. Although toxic chemicals can occur naturally, they can pose a hazard extending far beyond their source, if the weathering products become airborne, as is common in arid regions. For example, Owens Valley in eastern California is now recognized as the most significant source of toxic alkali dust in the western U.S. Understanding the spatial distribution of sources of naturally occurring toxins, the spread of contaminants from these source areas, and the correlation of contaminant distribution events with atmospheric winds and soil moisture (which controls susceptibility to wind shear) is possible through imaging spectroscopy.

By combining determination of soil composition and moisture from imaging spectroscopy with other measurements, such as high-resolution topography and precipitation, we may be able to achieve real-time prediction of short-term surface-change events such as landsliding. Liquid water absorption in highly susceptible super-saturated soils, as well as seasonal, fire-induced, or human-induced changes in vegetation and related soil strength, are key determinants of landslide susceptibility that can be revealed via spectroscopy. In order to quantify snow accumulation, snowmelt, and surface runoff where winter snows persist, simultaneous, real-time measurement via imaging spectroscopy of the three phases of water in melting snow and ice provides an otherwise unattainable window on the causative factors of major spring floods. Frequent observations from space are required for such transient situations.

The measurement of subtle differences in the mineralogy of surface rock and soil units serve to delineate the surface expression of earthquake faults. These same types of measurements can identify those naturally occurring minerals that acidify water and mobilize toxic heavy metals in water sources. Many materials in nature are harmful to man and often occur near population centers. The molecular absorption of a range of asbestos minerals, for instance, has been measured with AVIRIS in both natural and human-altered environments. For asbestos and other spectrally unique materials, spatial concentrations of less than one percent of a pixel can be resolved. The key characteristics required to enable such results are a high signal-to-noise ratio, stability of the instrument's radiometric and spectral calibration, and orthogonal spatial and spectral characteristics (such that all wavelengths for a given spectrum come from the same area on the surface).

In the solar-reflected spectrum, imaging spectroscopy of the solid Earth from space has taken an important first step with the Hyperion technology-demonstration sensor on the New Millennium Program Earth Observing (EO-1) spacecraft. Although Hyperion has a signal-to-noise ratio about one-fifth that of airborne AVIRIS, the success of its imaging capabilities and analysis of its limitations will aid the development of the next-generation spaceborne imaging spectrometers.



Much of the solar reflected, mid-wave infrared, and thermal infrared portions of the electromagnetic spectrum are transmitted through the atmosphere. Separating the molecular absorption and constituent scattering signatures in the spectra of surface rock and soil minerals, illustrated here for four common minerals, permits surface composition information to be recovered from high-resolution imaging spectroscopy.

The thermal portion of the spectrum includes important spectral signatures for Earth-surface materials. In addition to silicate mineralogy, changes in biota, soil water saturation, volcanic gas composition, and temperature can be discerned with appropriate spectroscopic measurements. Multispectral thermal-infrared measurements are being acquired by ASTER on the Terra platform. To address the challenges for solid-Earth science and hazards research with observations over this portion of the spectrum, substantially improved spectral sampling and high precision are required.

Acquisition of high-spatial-resolution panchromatic imagery in conjunction with imaging spectroscopy measurements will support the ability to measure and monitor small-scale surface displacements in a manner complementary to InSAR observations. Significant improvements in accuracy over what can be achieved with current NASA imagery require resolutions of 1–5 m/pixel.

The power of imaging spectroscopy is the ability for one technique to provide key data to solve a variety of problems, both within and outside of solid-Earth science. These data include ones that are relatively long lasting, such as images of zones of hydrothermally altered rocks or fault zones, and ones that are rapidly changing, such as measurements of soil saturation or airborne dust clouds. High spatial resolution is needed to delineate the persistent, but spatially complex, features of the Earth’s surface, whereas high temporal resolution is required to predict, track, and mitigate most natural hazards. As the field advances and problems become more specific, imaging spectroscopy missions must evolve to meet the diverse requirements of a broad variety of scientific targets. NASA has guided the technique from the laboratory to airborne experiments and finally to space. Future spaceborne missions should focus on meeting science-specific requirements for signal-to-noise ratio, spectral and spatial resolution, and temporal sampling.

To address the challenges for solid-Earth science, measurement requirements and suggested mission phasing are:

• *Immediate (1–5 years)*: Continued spaceborne and airborne imaging in the solar-reflected portion of the spectrum. An airborne capability in the thermal portion of the spectrum (3–5 μm and 8–12 μm with 30-nm spectral sampling) should be developed.

• *Near term (5–10 years)*: An improved-precision solar-reflected spaceborne imaging spectrometer with a 100-km swath and 30-m spatial resolution. A high-spatial-resolution panchromatic capability should be included. A thermal imaging spectrometer (3–5 μm and 8–12 μm with 30-nm spectral sampling) having high signal-to-noise ratio, good calibration stability, and spectral–spatial orthogonality should be flown as a space demonstration project.

• *Long term (10–25 years)*: Continuous spaceborne, wide-swath, full-spectrum, high-performance imaging spectroscopy. There should be a nested narrow-swath, high-spatial-resolution, full-spectrum capability to target transient events.

6. Space Geodetic Networks and the International Terrestrial Reference Frame

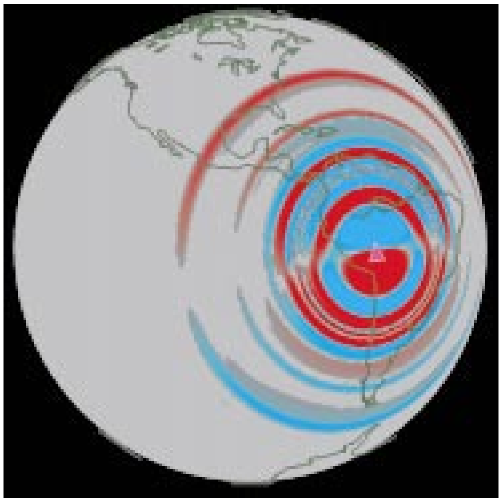
In cooperation with many international partners, NASA's Solid Earth Science Program plays a key role in establishing, maintaining, and operating global geodetic networks. Currently the networks include SLR, VLBI, and the GPS ground system. Relevant data products and valuable services are provided to the worldwide research community through the International Laser Ranging Service, the International VLBI Service, and the International GPS Service, respectively. Precise 3-D crustal motions are determined by all three networks, with dense GPS arrays particularly useful for regional tectonic and earthquake cycle studies. Beyond their scientific value, these data, together with precise determination of the 3-D geocenter motion by SLR and GPS, constitute the geodetic elements that define the International Terrestrial Reference Frame (ITRF), which is the basis for all geodetic measurements described in this report. The ITRF is geometrically connected to the Celestial Reference Frame via Earth Orientation Parameter (EOP) time series, which are determined primarily by the VLBI technique and contain a wealth of geophysical and climatic information. The ITRF and EOP, and hence the networks, should continue to be maintained and improved and their data routinely acquired at the best possible accuracy and temporal resolution.

7. Promising Techniques and Observations

A number of other promising observations that are either developing or expanding into the field of solid-Earth science offer additional methods to achieve the goals of the Solid Earth Science Program.

Seismology from Space

The SESWG is intrigued by the possibility of seismic imaging from space. Spaceborne seismology is a logical extension of spaceborne surface-change detection by SAR, radar, and GPS. The Southern California Integrated GPS Network (SCIGN) has observed near-field strain-wave propagation from the 1999 Hector Mine earthquake. It is likely that a continuously observing spaceborne system could image the occurrence of "silent" or "slow" earthquakes as well as the propagation of ground displacement by surface waves at scales of continents. The required technology, such as 30-m lightweight antennas, warrants early investment, and the specific data requirements for imaging from geosynchronous orbit should be defined. Another approach would be to use the ionosphere as a proxy for surface motion. It has been known for decades that the ionosphere responds to vertical motions of the Earth's surface with an amplification of the vertical surface displacement on the order of ten thousand, although very limited in frequency content. Whether ionospheric tomography from GPS limb sounding and ground GPS networks, along with magnetic constellations, could image these surface-wave-induced ionospheric gravity waves should be explored.



Propagation of seismic waves from the deep, magnitude 8.2 Bolivia earthquake of June 9, 1994. The earthquake was so large that it produced a permanent displacement of the surface of the Earth of several millimeters near the epicenter in Bolivia.

The Solid Earth Beneath the Oceans

Over 70% of the solid Earth lies beneath the oceans, and many geologic processes of global significance occur on and beneath the ocean basins and margins. Some of these processes have analogues on land, but others are quite distinct. For example, at more than 50,000 km in length, the global mid-ocean ridge system is the dominant contributor to volcanic activity at the Earth's solid surface. Mid-ocean ridges are the locus as well of pervasive hydrothermal systems that host unique biological communities not found at terrestrial volcanoes. Subduction zones, where great faults mark the sites of convergence between two tectonic plates, are found almost exclusively beneath the seafloor. Tsunamis, with their frequently devastating effects at coastal regions, originate by motion at the Earth–ocean interface.

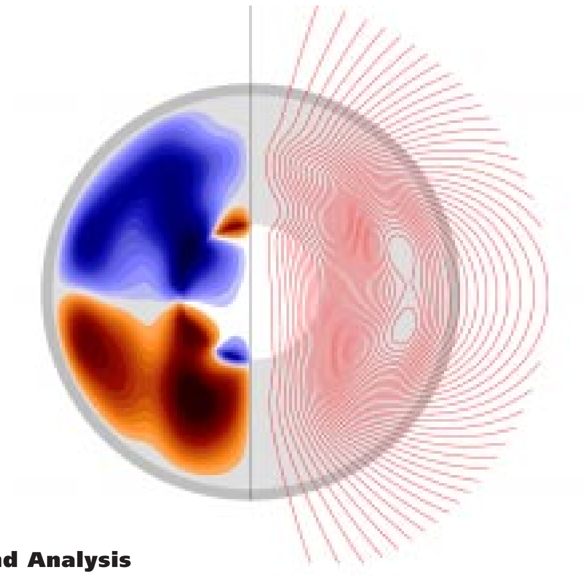
Spaceborne observations have made significant contributions to the study of the solid Earth beneath the oceans. This generalization has been especially true in geodesy and seafloor mapping. Space geodetic techniques based on GPS combined with precise (centimeter-level) acoustic ranging provide the only means to place deep ocean benchmarks in an absolute reference frame, and hence integrate seafloor plate motions into the terrestrial (e.g., VLBI) deformation field. Satellite altimetry has been used to infer seafloor bathymetry from linear inversion of the global gravity field. While the resulting product has lower spatial resolution than can be achieved with shipborne swath-mapping systems, it has provided the first global view of the shape of the ocean floor and the first comprehensive coverage in the remote southern oceans.

Future satellite missions will extend observations of the solid Earth beneath the oceans to smaller spatial scales and will enhance global understanding of temporal variability. For example, high-accuracy gravity measurements from GRACE follow-on missions might be capable of observing intermediate-wavelength gravity anomalies generated by the accumulation of strain at locked convergent margins. Making such measurements in situ is costly and dependent on the serendipitous concurrence of seafloor instrumentation with tectonic activity. Although some solid-Earth missions will have limited application to submarine processes, NASA should be watchful for future opportunities to ensure that spaceborne measurements are utilized to their full capacity.

Over the coming two and a half decades, the biological, chemical, and geological oceanography communities will increasingly focus on understanding episodic oceanic processes through the use of seafloor observatories. These will of necessity focus on the intensive study of relatively small regions, ranging from the scale of a mid-ocean ridge vent field up to that of the smallest (e.g., Juan de Fuca) tectonic plate. Spaceborne measurements that resolve temporal changes in the solid Earth beneath the seafloor will provide an essential global dimension to seafloor observatory efforts and should be coordinated with planned and future ocean observatory programs.

Subsurface Imaging

Spaceborne subsurface imaging was first demonstrated in radar images from the Spaceborne Imaging Radar (SIR-A and SIR-B) missions, from which sub-Saharan drainage channels were identified beneath desert sands. Applications of this capability range from the estimation of ice cap thicknesses to the determination of subsurface properties such as geological structure, lithology, and soil moisture. Radar subsurface imaging combined with hyperspectral imaging could prove extremely valuable for remotely mapping shallow subsurface characteristics that would make a region more vulnerable to natural hazards. For example, the capability to recognize areas of soft sediment or high moisture content could help delineate regions prone to strong shaking or possible liquefaction during earthquakes. Liquefaction effects after earthquakes have already been observed remotely in visual bands. Presently VHF or UHF sounding or SAR is the technology most often chosen as the means to achieve subsurface imaging. Advanced processing methods, improved hardware, airborne trials, and ground-truth procedures will need to be developed to capitalize on the promising potential that this approach offers for both basic and applied research.



Numerical models of the geodynamo are now capable of reproducing many details of the geometry of the Earth's magnetic field. Shown is a cross section of a model for the axisymmetric part of the magnetic field through the Earth's core along the rotation axis. The white innermost region is the inner core, the light gray region is the outer core, and the thin dark-gray region is the lowermost part of the mantle. The left half of the image depicts the strength of the toroidal (east-west) part of the field, which is directed eastward in one hemisphere and westward in the other. The right half shows field lines of the poloidal part of the field, which displays a nearly dipolar structure. The dynamo maintains the Earth's magnetic field by converting poloidal field into toroidal field, and then converting toroidal field back into poloidal field.

Research and Analysis

Data analysis is an essential part of every NASA space mission. Not only are NASA data of greatest benefit when integrated with quantitative models, but the research leads to new ideas for how Earth processes operate, new ways of making measurements from space, and new concepts for missions. The solid-Earth system is inherently complex, and understanding it requires significant effort in the analysis of data and their comparison with models. Simulations must be carried out concurrently with data analysis so that the entire system can be studied and understood. Observational data can also be assimilated into computational models providing constraints on and verification of hypotheses.

A few examples of critical research and analysis programs for solid-Earth science at NASA include the following:

• Models of crustal deformation that incorporate InSAR and GPS measurements of surface deformation. The models for plate boundary zones should include the pre-, co-, and postseismic phases of the seismic cycle. Models must be developed for the many other sources of surface deformation including those associated with volcanic eruptions, water withdrawal, and loading and unloading by water and ice.

• Models of landform evolution that account for time-dependent topography. The models should include the tectonic growth of topography as well as erosional processes.

• Models of time-dependent surface gravity. The models should account for tectonic, hydrological, surface loading and unloading, and mantle dynamical effects.

• Models of the Earth's magnetic field that account for observations.

Many solid-Earth science processes are associated with self-organizing complex systems and span time scales from seconds to tens of millions of years. A characteristic of these systems is that they satisfy self-similar, power-law statistics. Because this self-similarity extends over wide ranges of temporal and spatial scales, renormalization-group approaches are often required. These systems are generally chaotic, so they are statistical and intrinsically unpredictable. Examples include mantle convection, the outer core flow responsible for generating the Earth's magnetic field, the deformation of the Earth's crust responsible for earthquakes, and the evolution of land drainage systems.

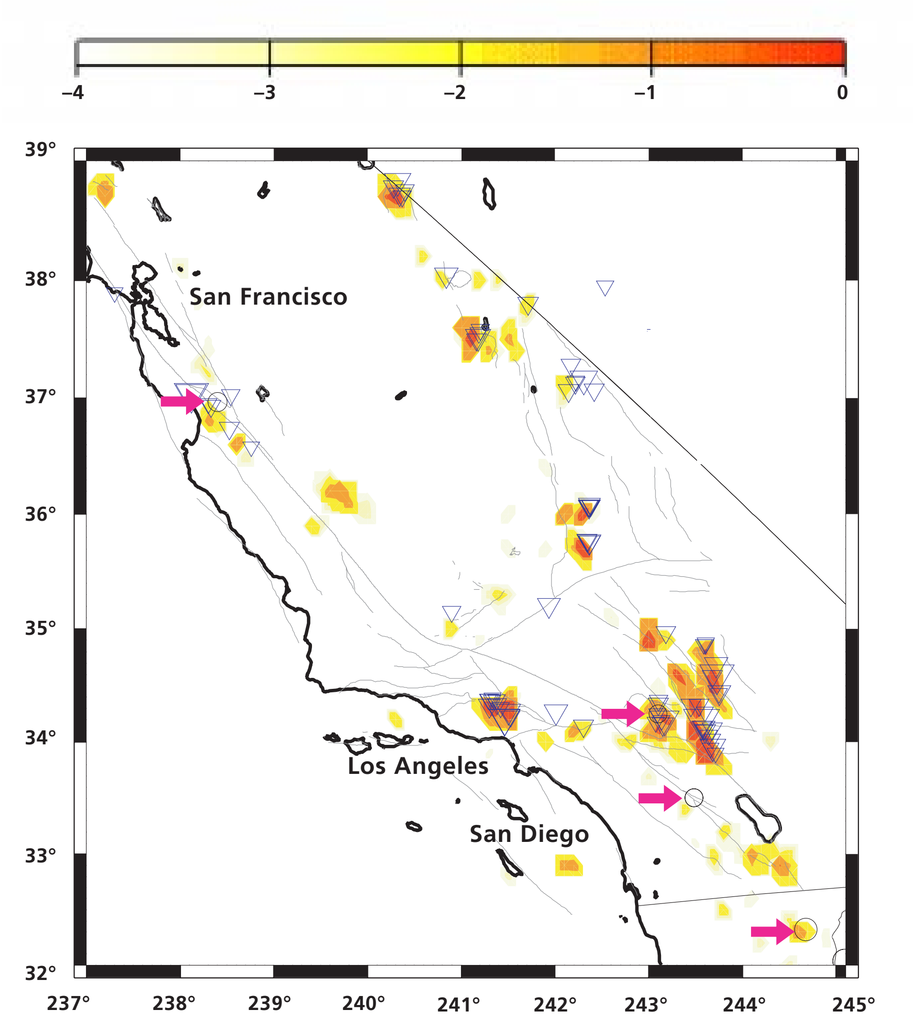
A number of natural hazards fall into this class of phenomena, including earthquakes, landslides, and forest and wild fires. Each of these natural hazards is characterized by a power-law distribution of severe "events." In order to explain this behavior, statistical physicists have introduced a number of simple cellular-automata models that yield power-law distributions of "avalanches." Three of these models can be directly associated with natural hazards: the slider-block model with earthquakes, the sandpile model with landslides, and the forest-fire model with large fires. The use of these models can provide a rationale for understanding and integrating a wide range of observational data on these systems.

Information Systems

1. Modeling and Computational Priorities

The broad range of spatial and temporal scales manifested by solid-Earth processes calls for a variety of modeling and data assimilation techniques. Advances in inversion methods, three-dimensional modeling, data assimilation, statistical analysis, and pattern recognition are all necessary for understanding these complex systems. High-performance computers are required for carrying out these approaches.

One of the major problems facing scientists today is that the scientific data volumes are increasing at a faster rate than computational power, challenging both the analysis and the modeling of observations. Resources must be put into improved algorithms to



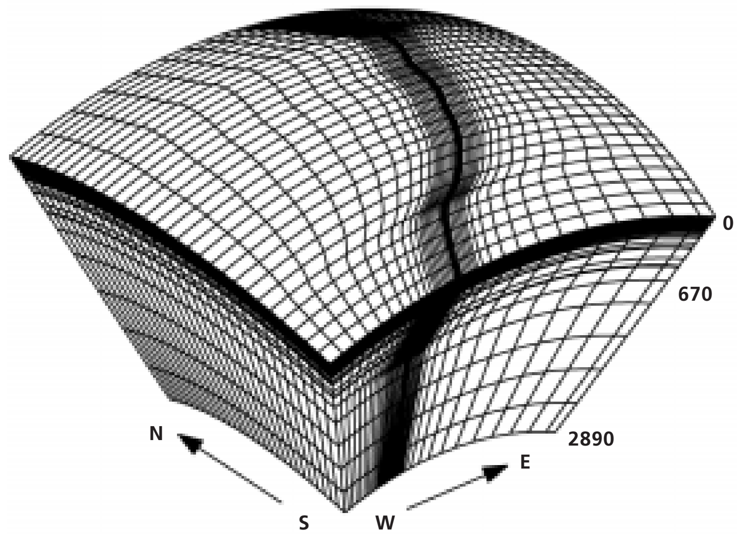
It is very difficult to forecast an earthquake. Yet advances in modeling and computational simulation methods, combined with increasing computational power, have suggested several methods for finding precursory space-time patterns hidden in existing data sets. One example is shown at left, where the colored anomalies are spots where future large earthquakes are likely to occur according to the analysis. More research is needed to quantify how well we can localize these occurrences in time. The red arrows point to four earthquakes of magnitude 5 or greater that have occurred since the forecast plot was made: the northernmost is the magnitude 5.2 Watsonville event that occurred on May 13, 2002; the middle earthquakes are the 5.1 February 10, 2001, Big Bear event, and farther south, the 5.1 October 31, 2001, Anza event; the southernmost is the 5.1 February 22, 2002, Baja California event. If the occurrence of moderate to large earthquakes were governed by statistical laws characterized by a uniform probability distribution in the space of seismically active crustal areas, then the probability that all four events fall within 11 km (the spatial resolution) of a colored anomaly can be computed to be about P~.001.

simplify processing and to approximate complex phenomena to allow researchers to handle the large volumes of data as well as to find the dominant physics in a given data set. Another promising approach to handling large data volumes is to use pattern recognition to focus attention and point out subtle features in the data.

Because of the complexity of the solid-Earth system, high-performance computers are required for scientific progress. Computations of the systems being studied, from the geodynamo to interacting fault systems, take weeks to years to run on even the most capable of current workstations, making supercomputers the only means of modeling the systems. It is crucial to utilize the latest computational advances to make modeling an effective tool.

For example, numerical modeling of the geodynamo places extraordinary demands on currently available computational resources. Recent calculations have consumed

months to years of CPU time on supercomputers. Yet these numerical models operate far from the parameter regime of the Earth. There is the potential for great progress when computational resources reach the stage where data assimilation and sensitivity analysis become feasible. However, to achieve this goal will demand an entirely new approach to the provision of computational resources in the solid-Earth sciences, most likely with massive computational grids being made available.



A three-dimensional finite element grid for modeling mantle flow and crustal deformation along a subduction zone. Such modeling techniques are extremely computationally intensive.

2. Distributed Receiving and Processing Systems

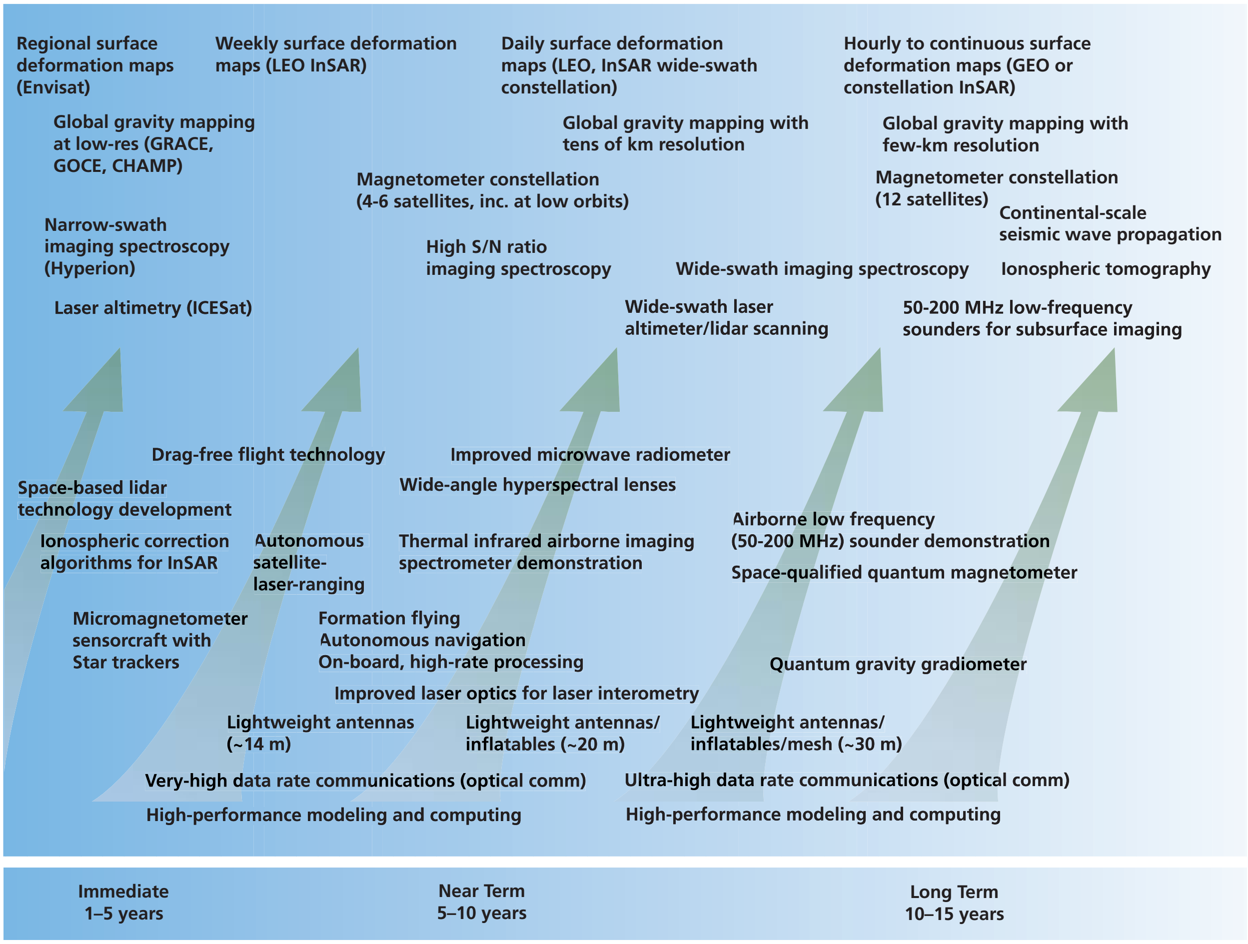
An important aspect of data collection is to create distributed centers for processing and storing unique data sets. Developing the infrastructure to compare and use complementary data sets, such as ice topography and sea-level changes, opens the door to interdisciplinary research. It is also important to create the infrastructure to access other non-NASA datasets such as seismic and geologic data. These supporting data sets are critical for modeling and understanding the complete system. These distributed data centers are particularly important in the event of natural disasters, when not only can they support disaster management but they also enable real-time scientific experiments dependent on time-sensitive observations. Such centers will become more important as multiple data types are fused into integrated models. Characteristics of a system of centers should include distributed data at thousands of sites, each with data volumes of 1 TB–1 PB; multitier architecture for staging of the data; middleware to control integrity and versioning; support standards developed within the community; and high-performance user access of 100-GB files from 40-TB data sets within 5 minutes and program-to-program communication in milliseconds using staging, streaming, and advanced cache replication.

Technology Development

The ambitious research agenda of the solid-Earth community will provide unprecedented levels of highly accurate data. To achieve the accuracies and the spatial and temporal resolution needed to answer the highest-priority questions about the solid Earth, however, will require new advanced spaceborne technologies. Several promising technologies lie just beyond current capabilities. Systematic development of technologies through the Earth Science Technology Office (ESTO), Advanced Component Technology Program (ACT), the Instrument Incubator Program (IIP), and the New Millennium Program (NMP) will help reduce the risk, development time, and cost of the target missions.

The new technologies that will result in the highest science payoff are summarized in the illustration below. Other enabling technologies will be identified in coming years, but the figure serves to show the importance of investing in technology to meet the requirements for future science return.

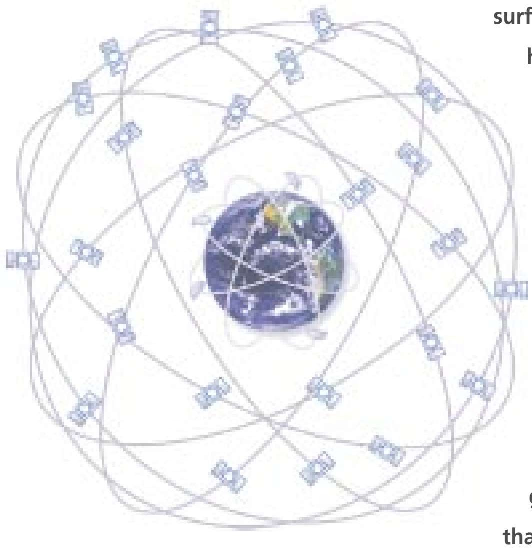
An early investment in technologies will enable critical future observations.



Supporting Framework

1. Maintenance of Global Geodetic Networks, Terrestrial Reference Frame, and Earth Orientation Parameters

The Global Positioning System constellation is used for measuring surface position changes to millimeter accuracy. Applications range from plate tectonic velocity measurements to search-and-rescue operations in remote locations. GPS is a critical part of the supporting framework for solid-Earth science research but plays a dual role as an operational network relied upon by a broad range of military and civilian parties.

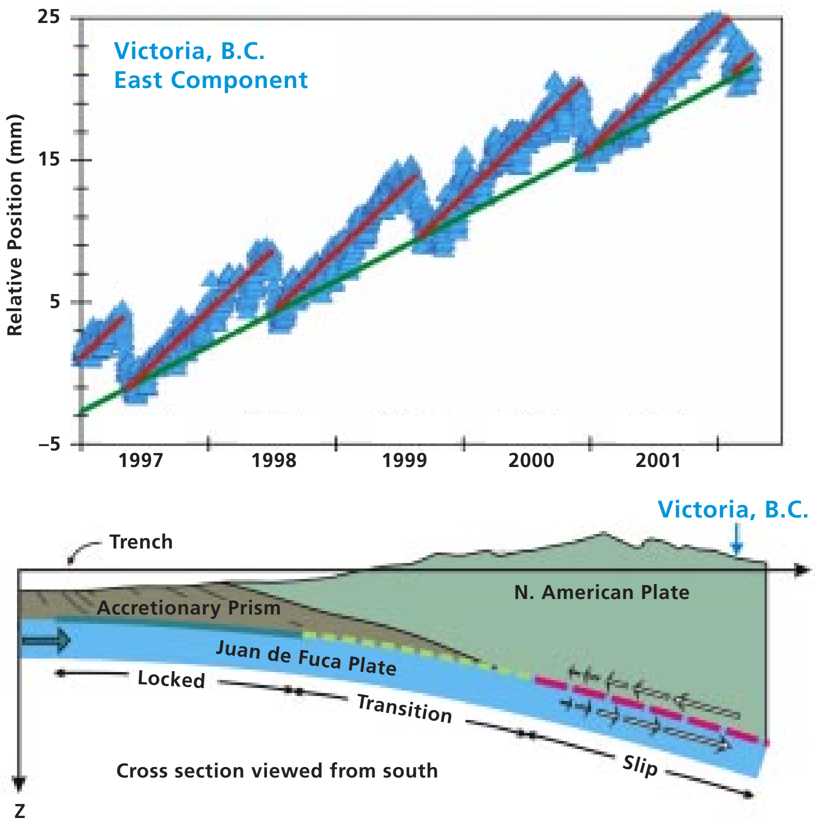


The accuracy of global geodetic networks advances by about a factor 10 per decade, with submillimeter-scale reference-frame accuracy likely in the near future. Continued improvements in accuracy are critical to a number of the recommendations of this report, from the study of sea-level change and improved gravity-field measurements to the detection and characterization of land surface change. The Internet and high-speed computing have recently been harnessed to provide near-real-time global GPS positioning and time transfer, of significant potential benefit to onboard satellite and airborne data reduction and natural hazards disaster management. For example, repeat-pass airborne InSAR is now possible given subdecimeter global navigation, a capability that can lead to real-time measurements of volcanic inflation and crustal deformation from an airborne platform. Temporal changes in the gravity field and their links to Earth-orientation parameters are also an important focus of ongoing research. For instance, recent increases in the equatorial oblateness of the geoid may signal the migration of water from polar regions toward the equatorial seas.

Although initiated by NASA's Crustal Dynamics Program to measure crustal deformation and changes in Earth's angular momentum, the global geodetic networks now provide critical data products and valuable services to a multitude of scientific, government, commercial, and military users well outside the solid-Earth science community through the International GPS Service, the International Laser Ranging Service, and the International VLBI Service. A significant challenge for NASA is to identify a mechanism by which the support for these vital resources can be shared by all users within the agency, so that NASA's Solid Earth Science Program can turn its attention to the development and implementation of the strategic recommendations of this report.

2. Precise Orbit Determination (POD)

As is well-recognized by its international partners, NASA's Solid Earth Science Program supports the development, maintenance, and continuing refinement and enhancement of computer software for modeling and computing satellite orbits. This precise orbit determination (POD) capability is essential for the global space geodesy enterprise. Satellite-based geodetic techniques, such as SLR, GPS (including occultation and reflection experiments), microwave and laser altimetry, lidar, and SAR/InSAR all require continuous POD to accuracies within a decimeter to centimeter and better. These data also feed into the maintenance of the ITRF. Furthermore, the POD information constitutes primary data for solution of the Earth's gravity field. Single-satellite POD over the past four decades and recent spaceborne GPS satellite-to-satellite tracking have led to generations of steadily improving Earth gravity models used as a reference for a variety of civil, military, and research applications. POD is also a stringent requirement for planetary flights, space missions testing relativistic effects, and space VLBI. Relative POD from inter-satellite tracking (e.g., GRACE) provides improved measurement sensitivity and spatial resolution. Development of a "drag-free" system using onboard proof-mass technology will further POD and modeling capabilities.



GPS observations have documented that deformation across the Cacadia subduction zone in the Pacific northwest is governed by two processes acting on very different time scales.

Top: Change in relative east-west position between two GPS stations in British Columbia, one (Victoria) near the plate boundary marking the eastward subduction of the Juan de Fuca plate, and the other (Penticton) well inland on the stable North American plate. The long linear episodes of shortening (red lines) are interrupted at intervals of approximately 14 months by transients of opposite sign. The transients last 1–2 weeks and produce surface displacements of up to 5 mm. The average rate of shortening, the superposition of the two styles of deformation, is shown by the green line.

(Bottom) This deformation pattern has been modeled as the result of depth-dependent slip behavior along the interface between the two plates. The long-term shortening is attributed to the steady accumulation of stress across a shallow, locked portion of the subduction interface that lies off-shore. That stress appears to be released episodically by large thrust earthquakes at intervals of several centuries. The transient displacements are attributed to more frequent " silent earthquakes," episodes of slow slip that relieve stress along a deeper section of the plate interface but generate no seismic waves. The reason for the near periodicity of these transients is not known. Future space-based observations coupled with simulations involving models similar to that shown will aid in elucidating the underlying mechanics.

3. Coordination, Validation, and Calibration

While space-based measurements are inherently global in coverage, in many instances they are limited in their temporal or spatial sensitivity. For example, the spatial resolution of quantities derived from potential field measurements or their gradients will always be limited by the distance of a satellite from Earth's surface. The repeat times of satellites are often too long to resolve temporal variability at periods of hours to days, a problem that is worsened as orbit height is increased, e.g., in an effort to increase mission longevity.

In many instances, gaps in spatial and temporal coverage can be filled by utilizing other measurement platforms. Fine spatial resolution is often best achieved with land or seafloor arrays installed either semi-permanently or on a campaign basis. These arrays are typically focused on specific geologic features, e.g., the networks of seismic and GPS instruments along the San Andreas fault. Airborne SAR or imaging spectroscopy can provide smaller spatial and shorter temporal resolution of local features of special interest such as active volcanoes. Projects such as the Airborne Synthetic Aperture Radar (AIRSAR), AVIRIS, and the private industry GEOSAR illustrate the importance of airborne data collection. An important role for airborne programs is as technology testbeds for future radar techniques. Coordination of these efforts with space-based missions will yield a scientific return that exceeds the contribution from each measurement type and should be actively encouraged.

This three-dimensional perspective view of the volcanic island of Manam, Papua, New Guinea, was obtained by AIRSAR operated in its topographic mode. The volcano, one of the most active in the Pacific "Ring of Fire," was in the midst of a large eruption when this image was acquired. Lava flows and hot clouds of rock, ash, and gas known as pyroclastic flows are emitted from craters at the summit of the volcano and race down the valleys. Deposits from earlier flows appear orange and blue; forested slopes of the volcano appear in pink.

The atmosphere and oceans are a prominent source of signal for some space-based measurements. Examples include temporal gravity variations to be measured by GRACE and its follow-on missions or Earth rotation measurements to be made by future altimetric missions. Correction, validation, and calibration of these space-based observations will require in situ measurement of atmospheric and oceanic quantities before these data can be used to address solid Earth problems. Terrestrial-reference-frame measurements assist in separating out such signals. Removing the atmospheric and oceanic signals requires accurate models of the general circulation of the atmosphere and ocean combined with assimilated global in situ measurements. Calibration and validation of GRACE-like missions requires the contemporaneous measurement of fluctuations of seafloor pressure. In the past, these supporting measurements have often been neglected or eliminated to accommodate budget shortfalls. Lack of such supporting data, however, reduces confidence in space-based measurements and in some instances can lead to incorrect inferences due to inherent measurement inaccuracy. Greater attention to validation and calibration is urged for all future mission planning.

Education

The discoveries and new knowledge gained from over 40 years of Earth remote sensing conducted by NASA have revolutionized our understanding of how the Earth functions as a system. This growing understanding is increasingly needed to inform political and economic decisions of local, national, and global impact.

The solid-Earth perspectives on life on a restless planet highlighted by this report offer exciting and engaging possibilities for education. To capitalize on these opportunities, the Solid Earth Science Program will collaborate with the NASA Earth Science Enterprise Education Program to stimulate broad public interest, appreciation, and understanding of Earth's interrelated systems, and encourage young scholars to consider careers in science and technology.

The Solid Earth Science Education Program (SESEP) will develop educational activities based on the three objectives identified by the ESE: informal education, formal education, and a work-force initiative in Earth Science Applications.

Informal education is considered an "out-of-classroom" educational opportunity such as those found in museums, science and technology centers, and similar nonprofit education organizations that provide significant educational activities for learners of all ages. Planned program components in this area include contributing new solid-Earth content and playing a consultative role for current and future development of exhibits, displays, and other non-classroom activities. For example, the California Science Center noticed that children's attendance in their Plate Tectonics area was down, likely because of a lack of appreciation among children (and probably their parents) that plate tectonics affects their lives. SESEP's remedy will be to develop hands-on activities to show the connection between plate tectonics and earthquakes and to create an enjoyable family learning experience. For existing NASA center partners, such as the interactive museum The Dynamic Earth, SESEP will arrange guest lecturers during Family Science nights and coordinate participatory demonstrations of topics such as earthquake simulation. SESEP will contribute to the NASA Earth Science Enterprise Museum Support workshops and conferences targeting the needs of informal educators across the country. SESEP will also assist in the development of solid-Earth aspects of educational overviews and foster working relationships across the informal education network.

Formal education includes traditional classroom education from kindergarten through 12th grade, as well as undergraduate and graduate university programs. SESEP will support existing NASA and partner programs, such as the Global Learning and Observations to Benefit the Environment (GLOBE) program (field studies for students using GPS measurements), with the development of new resource materials for classroom teachers. SESEP will identify and supplement efforts for undergraduate and graduate research opportunities through NASA centers, universities having Memoranda of Understanding (MOUs) with NASA, and existing university programs that support solid-Earth education and research.

Students make measurements of hidden magnets beneath a blue cloth in an analogy to the method GRACE uses to measure the gravity field of mass distributions in the Earth. Educational programs such as these are crucial in engaging the public in shaping and sharing NASA's experience in exploration and discovery and in appreciating how advances in solid-Earth science contributes to people's daily lives.

The Work Force Initiative in Earth Science Applications is a professional work-force development program aimed at identifying and addressing requirements for enhancing job skills in Earth science and technology fields. SESEP will establish a contact list of undergraduate and graduate students who are involved in solid-Earth science and are interested in participating in research programs. This list will be shared within NASA and with other government and private organizations that may have future opportunities for the students. SESEP partners and scientists will speak at specific engagements and professional conferences aimed toward industry to raise awareness of ongoing solid-Earth science efforts and to expand participation.

The Solid Earth Science Education Program is designed to exert a current, progressive, and informative influence that fulfills NASA's ESE objectives and leverages other ESE initiatives. SESEP will be an important element of NASA's contribution to the national socio-economic and educational agenda and will promote synergy among NASA and non-NASA activities while establishing its unique role and contributions to furthering solid-Earth education.

Summary

Earth science as a discipline now recognizes the dynamic, interconnected nature of the Earth as a system. Each component — oceans, atmosphere, biosphere, and solid Earth — interacts with the others in ways only partially understood and over a broad range of time scales. The solid Earth is a dynamic and essential component of the Earth system. From the motions in the core that generate the Earth's magnetic field, through mantle convection, plate tectonics, volcanic eruptions, and land surface evolution, the solid Earth is always changing.

A primary goal of solid-Earth science is the assessment and mitigation of natural hazards that seriously threaten health, safety, national security, and economic viability. Space-based data acquired by NASA and other cooperating Federal agencies contribute heavily to our understanding and forecasting of volcanic eruptions, sea-level rise, floods, landslides, earthquakes, and other hazards. The 25-year vision of the Solid Earth Science Working Group (SESWG) is to understand natural and perturbed systems well enough to predict outcomes, consequences, and impacts.

Understanding the discrete events that shape the Earth, and from them building a complete picture of our planet's dynamics, requires views of the governing behavior at local, regional, and global scales. For many scientific issues, satellite-based observations are the primary practical means to obtain an adequate density of coverage. Integrating the complementary and often more intensive, local ground-based measurements into comprehensive predictive models requires a new generation of satellite measurements at temporal and spatial resolutions substantially superior to those made in the past.

Six broad scientific challenges have been identified as the highest in priority for NASA's Solid Earth Science Program for the next 25 years. These challenges are of fundamental scientific importance, have strong implications for society, are amenable to substantial progress through a concerted series of scientific observations from space, and build naturally on directions identified in the NASA Earth Science Enterprise Strategic Plan. The six science challenges are

• What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?

• How do tectonics and climate interact to shape the Earth's surface and create natural hazards?

• What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea-level change?

• How do magmatic systems evolve and under what conditions do volcanoes erupt?

• What are the dynamics of the mantle and crust and how does the Earth's surface respond?

• What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

These six challenges are guiding themes that should define the research objectives for solid-Earth science within NASA for the next two and a half decades. Each challenge, once met, offers a series of significant expected accomplishments and clear benefits to the nation. On the basis of current knowledge, the next steps needed to address each challenge can be readily defined.

The six scientific challenges are also extremely ambitious and address goals common to the entire solid-Earth science community. Success in meeting these challenges will depend on the close coordination and collaboration with other NASA programs, with other federal agencies, and with international partners.

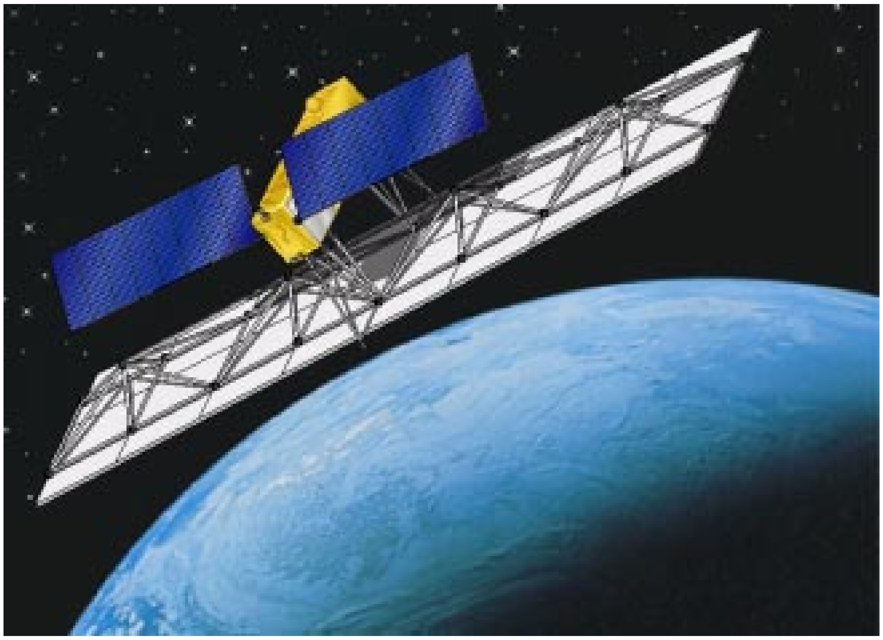
To make substantial progress toward answering each of the six challenges, NASA must formulate a broadly conceived program with both near-term goals and clear steps toward longer-term objectives. A fully realized program contains elements that encompass not only new observations, but also sustained investment in research and analysis, information systems, new technologies, supporting infrastructure, and education. While NASA's role in observations is primarily the development of satellite missions, such projects cannot be their most effective without complementary terrestrial observations and the requisite partnerships with other programs and agencies. A dedicated research and analysis program is critical to insure that newly acquired data are fully analyzed, to provide the new ideas for instrument and mission development, and to foster unexpected scientific discoveries. This effort should include significant investments in computation and modeling for testing theories and predictions. A number of observations needed over the next two decades require a continuing investment in advanced technology development. A modular yet broadly interlinked program architecture offers flexibility to change as scientific discoveries and programmatic requirements dictate.

The recommended plan for new observations from space to meet the scientific challenges for solid-Earth science builds on current capabilities and on data from missions and instruments that have recently flown, are currently flying, or are planned for the very near future. It also relies on data from missions currently supported by other scientific disciplines within NASA, and it leverages collaborations with federal, private, and international partners.

The plan is cast in terms of five observational campaigns or strategies, each of which addresses multiple scientific challenges. These strategies include

• deformation of the land surface,

• high-resolution topography and topographic change,



A dedicated InSAR satellite is the highest-priority objective for solid-Earth science at NASA in the next 5 years.

- variability of the Earth's magnetic field,
- variability of the Earth's gravity field, and
- imaging spectroscopy of Earth's changing surface.

Specific recommendations for each strategy are divided by time horizon among the immediate time frame (1–5 years), the near term (5–10 years), and the long term (10–25 years). Supporting strategies are offered for space geodetic networks and the International Terrestrial Reference Frame, as well as for several promising directions where substantial technology development will be required.

The elements of these observational strategies, broken down by time frame, are illustrated in the table on page 60. The potential impact of each strategy on each of the six scientific challenges is also indicated.

In the next 5 years, the new space mission of highest priority for solid-Earth science is a satellite dedicated to Interferometric Synthetic Aperture Radar (InSAR) measurements of the land surface at L-band. Such a mission would address the most urgent objectives in the areas of plate-boundary deformation, land-surface evolution, ice and sea-level change, volcanism, and mantle dynamics.

Over the next 5–10 years, the scientific challenges facing solid-Earth science can be met by NASA leading or partnering in the flight of space missions involving constellations of satellites dedicated to InSAR and magnetic field measurements, new-generation instruments for mapping global topography and its temporal changes and for carrying

Timeline / Observational Strategies	Immediate (1–5 Years)	Near Term (5–10 Years)	Long Term (10–25 Years)	Plate Boundaries	Land Surface Change	Ice and Ocean Dynamics	Magmatic Processes	Mantle Dynamics	Magnetic Field
Surface deformation	Single dedicated InSAR satellite • L-band, left/right looking capability, and weekly access to anywhere on the globe • Precise orbit determination and ionospheric correction capabilities • 1 mm/yr surface displacement over 50-km horizontal extents in selected areas	Constellation of InSAR satellites • Improved temporal frequency of deformation maps to daily intervals • Maps at several-hundred-km width with full vector surface displacements at accuracies of submillimeter per year over 10-km spatial extents and 1-m spatial resolution • Complementary ground and seafloor geodetic observations	Constellation of InSAR satellites in low-Earth or geosynchronous orbits • Hourly global access • Increased density of continuous ground and seafloor geodetic observations						
High-resolution topography	Distribute all SRTM data, launch ICESat, and demonstrate imaging lidar capabilities in Earth orbit	Global mapping to supercede the SRTM data set • One-time global mapping at 2- to 5-m resolution and 0.5-m vertical accuracy for the ground surface • Ice-sheet mapping with 1-km horizontal resolution, 1-cm vertical accuracy for the ice or snow surface, and a repeat interval of months (for annual changes) to years (for long-term changes)	Continuously operating, targeted, high-resolution topographic mapping and change-detection capability • Targeted local to regional mapping, with global access, at 1-m resolution, 0.1-m vertical accuracy for the ground and water surfaces • Repeat frequency of hours to years depending on the rate of topographic change						
Variability of Earth's magnetic field	Support of analysis of geomagnetic observations from current satellites • Development of a modularized instrument package to facilitate taking advantage of missions of opportunity	Constellation of 4–6 satellites • At a range of local times • Approximately 800-km altitude in polar orbit	Complete, 12-satellite constellation • Adding satellites at lower altitude (300 km) in polar orbit (to enhance study of the crustal field) • At 800 km in a low-inclination orbit (to enhance recovery of mantle electrical conductivity) • Technological advancements on incorporating star trackers on magnetometers and improved lifetimes at low altitudes						
Variability of Earth's gravity field	GRACE • Monthly estimation to within a few millimeters of surface water-equivalent load at a few-hundred-kilometers spatial resolution	GRACE follow-on mission • Demonstration of satellite-to-satellite laser interferometry technology	Gravity measurement improved by 2–3 orders of magnitude in sensitivity • Satellite-to-satellite laser interferometry, or • Spaceborne quantum gradiometer						
Imaging spectroscopy of Earth's changing surface	Continued spaceborne and airborne imaging in the solar reflected spectrum • Develop airborne measurement capability in the TIR (3–5 and 8–12 micrometers)	Improved spaceborne imaging spectrometer • 100-km swath and 30-m spatial resolution in the VNIR • Demonstration of spaceborne TIR imaging spectrometer: 30-km swath, 30-m spatial resolution	Continuous full-spectrum spaceborne imaging spectrometry • Targeted local to regional mapping, with global access, across multiple wavelengths • Repeat frequency of hours to years, depending on the rate of change of the studied process						

Scientific Challenges	Color Code	Examples of the Benefits to Society
What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?		Rapid response to seismic disasters
How do tectonics and climate interact to shape the Earth's surface and create natural hazards?		Floods, landslides, and coastal erosion risk assessment
What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea-level change?		Improved estimates of future sea-level rise
How do magmatic systems evolve and under what conditions do volcanoes erupt?		Advanced planning for high-risk populations near volcanoes
What are the dynamics of the mantle and crust and how does the Earth's surface respond?		Understanding mantle and crustal dynamics role in hazards
What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?		Forecasts of magnetic field for space weather effects on satellites

out imaging spectroscopy across a broad portion of the electromagnetic spectrum, and a GRACE follow-on to improve the resolution of temporal changes in Earth's gravity field.Several techniques and observations offer the promise to contribute in a major fashion to solid-Earth science but require substantial technology development. Among these are imaging of propagating seismic waves from space, linking space observations to processes occurring on and within the solid Earth beneath the oceans, and subsurface imaging from space with ground-penetrating radar.

The solid Earth is inherently complex, and understanding it requires significant effort in the analysis of data and their comparison with models. Simulations must be carried out concurrently with data analysis so that the entire system can be studied and understood. High-performance computers dedicated to solid-Earth science are required to carry out these calculations, as well as to manage the large volumes of scientific data that the recommended observational strategies will yield. Distributed centers are the preferred mode for processing, storing, and retrieving the needed data. Each observational strategy calls for new technologies, and the time frames when each new technology will be needed dictate the level and pace of required investment. All of the recommendations for solid-Earth science are predicated on maintaining NASA's special capabilities in updating the terrestrial reference frame, monitoring Earth orientation parameters, and carrying out precise orbit determination. Each recommendation also calls for ground-based validation and calibration measurements that are closely coordinated with the spaceborne observations. Finally, the expected new knowledge to be gained about the solid Earth and its natural hazards provides compelling material with which to inform and engage students at all educational levels.

The beginning of the 21st century is a time of unprecedented opportunity in solid-Earth science. The confluence of advances in satellite-based observing systems, high-performance computing and communications, and recent fundamental discoveries, all over the past few decades, promises an era in which many of the previously seemingly intractable problems in Earth science are now ready to be solved. In the next two decades we will be in a position to reach new insights into earthquakes, volcanic eruptions, wildfires, landslides and floods, and the dynamics of the Earth's core and mantle. NASA has a unique and essential role to play in seizing this opportunity to understand and manage the restless planet on which we all live.

Credits

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